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Recovery of the orbital parameters and pulse evolution of V0332+53 during a huge outburst

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ABSTRACT

The high mass X-ray binary (HMXB) V0332+53 became active at the end of 2004, with the outburst being monitored by RXTE and INTEGRAL at hard X-rays. Here, the orbital parameters are measured with the hard X-ray data through the fitting of the Doppler-shifted spin periods. The derived orbital period and the eccentricity are consistent with those reported by Stella et al. (1985) from earlier EXOSAT observations, whereas the projected semimajor axis and the periastron longitude are found to differ, from 48±4 to 86^{+6}_{-10} lt-s and from 313°±10 to 282°±14, respectively. This would indicate an angular speed of $\geq$ 1.6°±0.9 yr^{-1} for the orbit over the past 20 years. The periastron passage time, TJD 13367±1, is just around the time when the intensity reached the maximum and, an orbital period earlier is the time when the outburst occurred. This correlation resembles the behavior of a Type I outburst. During the outburst the source spun up with $\dot{P}_{spin}$=$8.01^{+1.00}_{-1.14}\times10^{-6}$ s day^{-1}. The evolution of the pulse profile is highly intensity dependent. The separation of the double pulses kept almost constant ($\sim$ 0.47) when the source was bright, and dropped to 0.37 within $\leq$ 3 days as the source became weaker. The pulse evolution of V0332+53 may correlate to the change in the dominance of emission between fan-beam and pencil-beam mechanisms.

Subject headings: Key wards: stars: X-rays: binaries – X-rays: sources

1. INTRODUCTION

In the history of HMXB V0332+53 observations, outbursts in hard X-rays showed up four times. The first was a Type II outburst caught by Vela 5B in 1973, with a duration of $\sim$ 100 days and peak intensity of 1.6 Crab (Terrell and Priedhorsky 1984). A spin period of 4.37 s and an orbital period of 34 days were discovered (Whitlock 1989). The second outburst was detected by Tenma satellite 10 years later (Tanaka et al. 1983). The follow-up series of observations performed by EXOSAT showed the outbursts were Type I and measured the orbital parameters; e.g. a moderate eccentricity $\sim 0.31\pm0.03$ and a projected semimajor axis 48 ± 4 lt-s (Stella et al. 1985). Favored by the precise source location attained with EXOSAT, the companion was identified in the optical as an early-type star, BQ Cam (Honeycutt and Schlegel 1985), and the distance to the source was estimated to be 2.2–5.8 kpc (Corbet et al. 1986). V0332+53 was found to be active again by Ginga in 1989 (Tsunemi et al. 1989). The outburst was classified as Type II and a feature of 0.05 Hz QPO was reported (Takeshima et al. 1994). A cyclotron absorption component at 28.5 keV suggested that the magnetic filed could be as high as 2.5×10^{12} G on the surface of the neutron star (Makishima et al. 1990).

The most recent outburst was detected by the all-sky-monitor (ASM) of RXTE in November 2004. Target of Opportunity (ToO) observations were carried out by INTEGRAL at hard X-rays too. Three cyclotron lines were found in INTEGRAL data by Kreykenbohm et al. (2005), which confirmed the discovery by Coburn et al. (2005) in RXTE data. The intensity averaged on December 22 was about 1.2 Crab in the 1.5–12 keV band and 2.2 Crab in the 5–12 keV band. An additional QPO feature was discovered from the PCA data of RXTE to ride on the spin frequency (Qu et al. 2005). In this letter we report the measurement of the current orbital parameters as obtained with RXTE/INTEGRAl data and the trend of pulse evolution with time.

2. OBSERVATIONS AND ANALYSIS

The public data we have analyzed are shown in Figure 1 for PCA/RXTE and INTEGRAL observations on V0332+53 during its outburst. The PCA/RXTE data are collected within time periods of December 28-30 in 2004, January 5-6, 15-19, February 12-15, and March 7 in 2005. The typical exposure of individual observation are several thousand seconds and the neighboring observations are combined to have the largest time span of roughly half day. The arrival time is corrected to the barycenter for each photon (2-60 keV).

INTEGRAL ToO observations are available for 9 revolutions during January - February 2005. ISGRI/IBIS data of revolutions 272-274 (pointings 75, 66 and 82) ($>$ 15 keV) are adopted in our analysis. The source intensity went down thereafter and INTEGRAL data of later revolutions does not allow precisely deriving the spin period. The revolution 272 was carried out in staring mode and the other two revolutions in hexagonal dithering mode. The total exposure considered is about 110 ksec for these three revolutions. To further improve the statistics, neighboring science windows of the pointing in each revolution are combined to enlarge the time span roughly 10^4 seconds. Data reduction is performed using the latest version (4.2) of the standard INTEGRAL Offline Science Analysis (OSA) software. The photons with pixel illuminated factor 1 are extracted and the arrival time is corrected to the barycenter (Chernyakova 2004).

3. RESULTS

3.1. Orbital parameters

The orbital parameters of the binary system can be measured through fitting the radial-velocity curve. The radial velocity (v_r) of orbital motion will modulate the spin period (P_{spin}) of the neutron star through the Doppler effect

$$P_{obs} = (P_{spin} + \dot{P}_{spin}\Delta t)\sqrt{\frac{1 + v_r/c}{1 - v_r/c}} \tag{1}$$

where $\dot{P}_{spin}$ is the change rate of the spin period and P_{obs} the observed spin period. The radial velocity can be represented by the orbital parameters as

$$v_r = K(\cos(\theta + \omega) + e\ \cos(\omega)) \tag{2}$$

where θ is the true anomaly at time t, ω the periastron longitude, e the orbital eccentricity, and K the so-called semi-amplitude of the velocity curve. The systemic velocity is not considered since the radial velocity profile is not modulated with a constant velocity. The angular position θ of the star at a given time t can be obtained by iteratively solving the equation

$$E - e\ \sin(E) = 2\pi(t - T_p)/P_{orbit} \tag{3}$$

where E is the eccentric anomaly, P_{orbit} the orbital period, and T_p the time of the periastron passage. K is written in the form

$$K = 2\pi\, a_x\ \sin(i)/(P_{orbit}\sqrt{1 - e^2}) \tag{4}$$

where $a_x \sin(i)$ is the projected semimajor axis along the line of the sight. Now we have 7 fundamental parameters to be inferred from fitting the P_{spin} curve. Equations 2-4 are taken from Hilditch (2001).

The spin period is searched in observational data by using the tool *efsearch* enclosed in the ftool software package. The resolution and the number of phase bins (N_b) are chosen as 1×10^{-6} s and 200, respectively. The derived $\chi^2 \sim P_{spin}$ curves were fitted by Gaussians, to estimate the most likely value of P_{spin}.[1] Its error is roughly taken to the first order as $P_{spin}^2/(T_{span}\,N_b)$, where T_{span} is the total time of observation, varying from 10^3 to 10^4 s. We note that the variation of the radial velocity within T_{span} is

$$\Delta v_r = -K\sin(\theta+\omega)\,\dot{\theta}\,T_{span} \tag{5}$$

where $\dot{\theta}$ is

$$\dot{\theta} = 2\pi\,(1-e^2)^{1/2}/(P_{orbit}(1-e\,\cos(E))^2) \tag{6}$$

For the first trial in fitting the data, the uncertainty in v_r is taken as $2\pi K T_{span}/P_{orbit}$, i.e., with zero eccentricity and other parameters coming from Stella (1985). The corresponding contributions to the error in P_{spin} are then taken into account accordingly. [2]

The reduced χ^2 for fitting the data is 0.9834 (26 dofs). The best-fit parameters for the eccentricity and the orbital period are $e = 0.373\pm0.1$ and $P_{orbit} = 34.67^{+0.35}_{-0.21}$, respectively, both are consistent within a 2σ error bar with those reported by Stella et al. (1985). The projected semimajor axis obtained from the fit results $86.4^{+6.2}_{-10.4}$ lt-s, and is significantly larger than 48±4 lt-s obtained in an outburst 20 years ago (Stella et al. 1985). With the updated orbital parameters, the contributions from the variation of the radial velocity to the error in spin period are then revised. The obtained spin periods from ISGRI/IBIS and PCA/RXTE are shown in Figure 2. The data are fit again and the best-fit parameters are shown in Table 1. The reduced χ^2 changes slightly to 0.9826 for 26 dofs. The 1 sigma errors are obtained by adding 8.1 to the minimum χ^2-value as is appropriate for 7 parameters of interest. The results are consistent within error bars with those obtained 20 years ago for parameters of eccentricity, orbital period, and spin period, but the projected semimajor axis and the periastron longitude differ. The neutron star passed through the periastron at the time when the source had the peak intensity. We find that the neutron star spun up with a rate of $8.01^{+1.00}_{-1.14}\times10^{-6}$ s/day during the outburst.

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[1] The last science window of pointing 75 in revolution 272 of ISGRI/IBIS and the PCA/RXTE data on March 9 2005 are not used since the resulting distributions in spin period are quite noisy.

[2] We have perfomed other trials as well, with different combinations of Stella's results. All obtained fits were worse than the one we find as a solution.

Table 1: Parameters for V0332+53

$a_x \sin(i)$	$86.36^{+6.10}_{-10.36}$ lt-s
P_{spin}	$4.37480^{+9\times10^{-5}}_{-5\times10^{-5}}$ s
P_{orbit}	$34^d.674^{+0.377}_{-0.236}$
K_x	58.5 ± 7.3 km s^{-1}
$f(M)$	$0.58 \pm 0.23 M_\odot$
e	$0.373^{+0.107}_{-0.117}$
ω	$282^\circ.53^{+14.30}_{-13.75}$
T_p	TJD 13367 $\pm$ 1
$\dot{P}_{spin}$	$-8.01^{+1.00}_{-1.14}\times10^{-6}$ s/day
$\dot{P}_{spin}/P_{spin}$	$-(1.83\pm0.23)\times10^{-6}$ yr^{-1}

3.2. Phase evolution

To obtain the absolute phase for the whole data one has to subtract the effect of orbital motion from the photon arrival time. The main uncertainty in such correction comes from that in (a $\sin(i)/c$) which could be as large as 6-10 seconds in our data and is insufficient for precisely obtaining the absolute phase at different times. We therefore co-align the phase by taking one of the two bridges for double-pulse light curves but arbitrary for light curve with single pulse (Figure 3). As shown in Figure 1, there are five data groups representing different intensity levels of the outburst. For each time period the typical light curves are plotted in Figure 3. The light curves are dominated by broad, asymmetric double pulses when the source was at high intensity level within TJD 13367-13376. The two pulses become narrower and symmetric as the source intensity went down to middle level in TJD 13386. Roughly 30 days later, when the outburst evolved to the tail, the two pulses started to move closer. As shown in Figure 1, the phase separation of the two pulses kept roughly constant (~ 0.47) when the source was bright, and dropped from 0.47 to 0.37 within less than 3 days (TJD 13413-13416) at low intensity level. In TJD 13436 the outburst almost ceased and only a single Gaussian-shaped pulse exists in light curve. The single pulse prevents from estimating the phase separation in the light curve. Nevertheless, a zero phase separation would be consistent with the trend as seen in the preceding data (see dashed line in Figure 1).

4. DISCUSSION

Some orbital parameters recovered from PCA (RXTE) and ISGRI/IBIS (INTEGRAL) observations on the recent outburst of V0332+53 change from those obtained in outbursts recorded 20 years ago (Stella et al. 1985). The projected semimajor axis has changed from 48±4 to 86^{+6}_{-10} lt-s and the periastron longitude decreases from 313°±10 to 282°±14, implying a rotation of the orbit with an angular velocity $\geq 1.6°\pm0.9$ yr^{-1} over the past 20 years. The motion of the orbital system with respect to the line of the sight may be caused by a variety of effects. The spin-induced quadrupole moment of a rapidly rotating star may change the orbital dynamics, and induce the motion of periastron and the precession of the orbital plane. Such effect is relatively small, $\leq 0.1°$ yr^{-1} was found in an investigation of the high mass neutron star binary system PSR J0045-7319 by Lai et al. (1995). Other effects like the static tide and those caused by general relativity are of one magnitude smaller. These effects may have different influence on the periastron motion in binary systems of different configuration. For those compact system with small orbital period (typically less than 1 day), the angular velocity of the periastron could be as large as several degrees - hundred degrees per year (Petrova and Orlov, 1999). For X-ray binary system with long orbital period, the largest rate of periastron motion observed so far may be in Vela X-1 with an angular velocity of 6.9°±3.4 yr^{-1} (Boynton et al. 1986).

The ratio of the projected semimajor axis between Stella's results and ours is 1.8. By assuming no change in semimajor axis and the inclination angle, this value would be inconsistent with that of 1.3 represented by the ratio of $\cos(X)$, where X is the angle between the semimajor axis and the x axis of the orbital system. The change in inclination angle, if any, would be constrained from the currently obtained orbital parameters. With a mass function of 0.58 $M_\odot$, binary system V0332+53 consisting of a companion of $\geq$20 $M_\odot$ and a neutron star of 1.44 $M_\odot$ would require an inclination angle of the orbit to be $\leq 18.9°$.

The periastron passage time of TJD 13367±1 is just around the time when the intensity reached the maximum and, an orbital period earlier is the time when the outburst occurred (∼TJD 13332, Swank et al. 2004). This correlation resembles the behavior of a Type I outburst. During the outburst a spin-up rate of $\dot{P}_{spin}$=$8.01^{+1.00}_{-1.14}\times10^{-6}$ s day^{-1} is derived. Such change in pulse period is generally regarded as the result of the interaction of the neutron star with the accreting matter. The corresponding relationship between $\dot{P}_{spin}/P_{spin}$ and the luminosity is $\dot{P}_{spin}/P_{spin}\sim$-$3\times10^{-5}P_{spin}L^{6/7}$ yr^{-1} (Rappaport and Joss 1977). Here P_{spin} and L are in units of second and 10^{37} erg s^{-1}, respectively. With the updated orbital parameters the luminosity is estimated to be $\sim5\times10^{37}$ erg s^{-1}. This value is consistent with the luminosity of (1.4-9.7)$\times10^{37}$ erg s^{-1} in 2-10 keV during December 24-26 2004, estimated assuming that the source is at a distance of 2.2–5.8 kpc (Soldi et al. 2005).

It is generally thought that XRB outbursts are powered by the accretion of the matter from the companion to the magnetic poles of neutron star. For luminosity $\geq 10^{37}$ erg s^{-1} the accretion flow onto the magnetic pole will be decelerated in a radiative shock above the neutron star surface (Basko and Sunyaev 1976). The photons will escape in a fan-beam from the emission region below the shocked region, and the peak emission is perpendicular to the magnetic axis. For luminosity lower than 10^{37} erg s^{-1}, a pencil-beam emission might be formed with the maximum along with the direction of the magnetic axis. During the outburst, emission from both components may contribute to the pulse profiles in the light curve. The study on the pulse profile evolution of EXO 2030+375 indicated that, as the luminosity decreased, the dominant emission changed from a fan-beam to a pencil-beam configuration (Parmar et al. 1989). The pulse evolution in V0332+53 may be understood in a similar way. At high luminosity, the pulse profile is dominated by the fan-beam component, showing double peaks separated in phase by $\sim$0.47. The luminosity at TJD 13416 went down to $\sim 1\times10^{37}$ erg s^{-1} and the contribution from an additional component, that of the pencil-beam, showed up in light curve at somewhere between the double pulses. At even lower intensity level, only pencil-beam emission persists, generating a single symmetric pulse in the light curve either because of a special geometrical configuration of the two magnetic poles or the cease of the flare in one of the magnetic poles. The combination of the single pulse from pencil beam to one of the double pulses from fan beam will lead to a broadened pulse and the visual phase separation of double pulses becomes smaller than previous. That the pulse separation decreased by 20 percent, from 0.47 to 0.37 within $\leq$ 3 days may constrain time scale of the transition in emission between different components when the burst evolved to a low intensity level.

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REFERENCES

Basko, M. M., and Sunyaev, R. A 1976, MNRAS, 175, 395

Boynton P.E., Deeter J.E., Lamb F.K., and Zylstra G. 1986, ApJ, 307, 545

Chernyakova M. 2005, 'IBIS Analysis User Manual'

Coburn W., Kretschmar P., Kreykenbohm I., et al. 2005, ATel, 381, 1

Corbert R. H. D., Charles P. A., van der Klis, M. 1986, A&A, 162, 117

Hilditch R.W. 2001, 'An Introduction to Close Binary Stars', Cambridge University Press, Pages 38, 42.

Honeycutt, R. K. & Schlegel, E.M. 1985, PASP, 97, 300

Kreykenbohm I., Mowlavi N., Produit N., et al. 2005, A&A, 433, L45

Lai D., Bildsten L., and Kaspi V.M. 1995, ApJ, 452, 819

Makishima K., Ohashi, T., Kawai, N., et al. 1990, PASJ, 42, 295

Parmar A.N., White N.E., and Stella L. 1989, ApJ, 338, 373

Petrova A.V., and Orlov V.V. 1999, AJ, 117, 587

Qu J.L., Zhang S., and Song L.M. 2005, ApJ, submitted

Rappaport S., and Joss P.C. 1977, Nature, 266, 21

Soldi S., Produit N., Belanger G., et al. 2005, ATel, No.382

Stella L., White N.E., Davelaar J., Parmar A.N., and Blissett R.J. 1985, ApJ, 288, L45

Swank J., Remillard R., and Smith E. 2004, ATel, No.349

Takeshima T., Dotani T., Mitsuda K., et al. 1994, ApJ, 436, 871

Tanaka, Y., and *Tenma Team.*1983, *IAU Circ.*, No. 3891

Terrel N.J., and Priedhorsky W.C. 1984, ApJ, 285, L15

Tsunemi H., Kitamoto, S., Manabe, M., et al. 1989, PASJ, 41, 391

Whitlock L. 1989, ApJ, 344, 371

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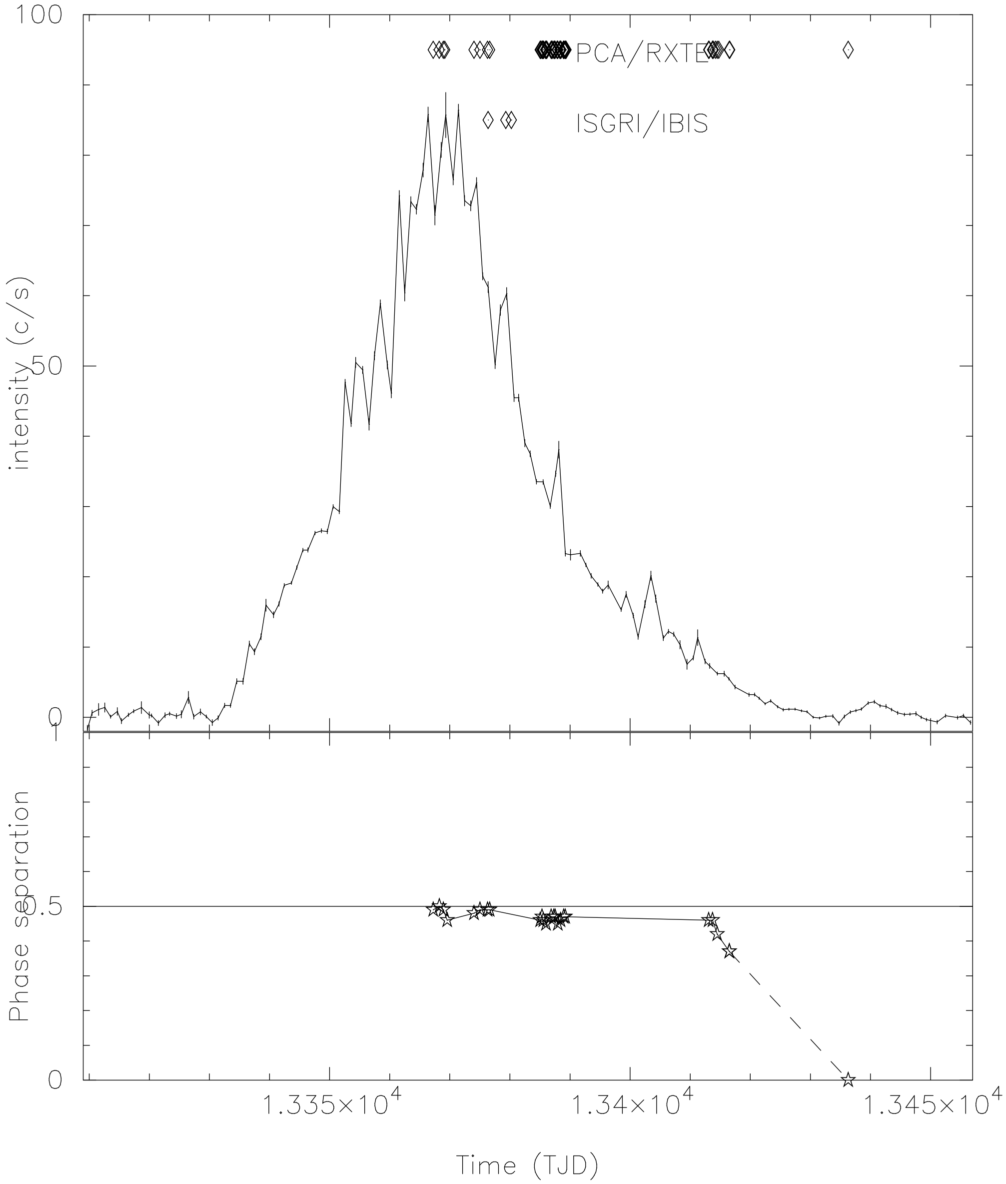

Fig. 1.— ASM light curve (1.5-12 keV, upper panel) and the phase separation of the pulses in light curve of V0332+53 during outburst (lower panel). On top of the light curve in the upper panel are over plots for PCA/RXTE and INTEGRAL observations analyzed in this paper. The dashed line in the lower panel shows the trend of extending to a zero phase separation.

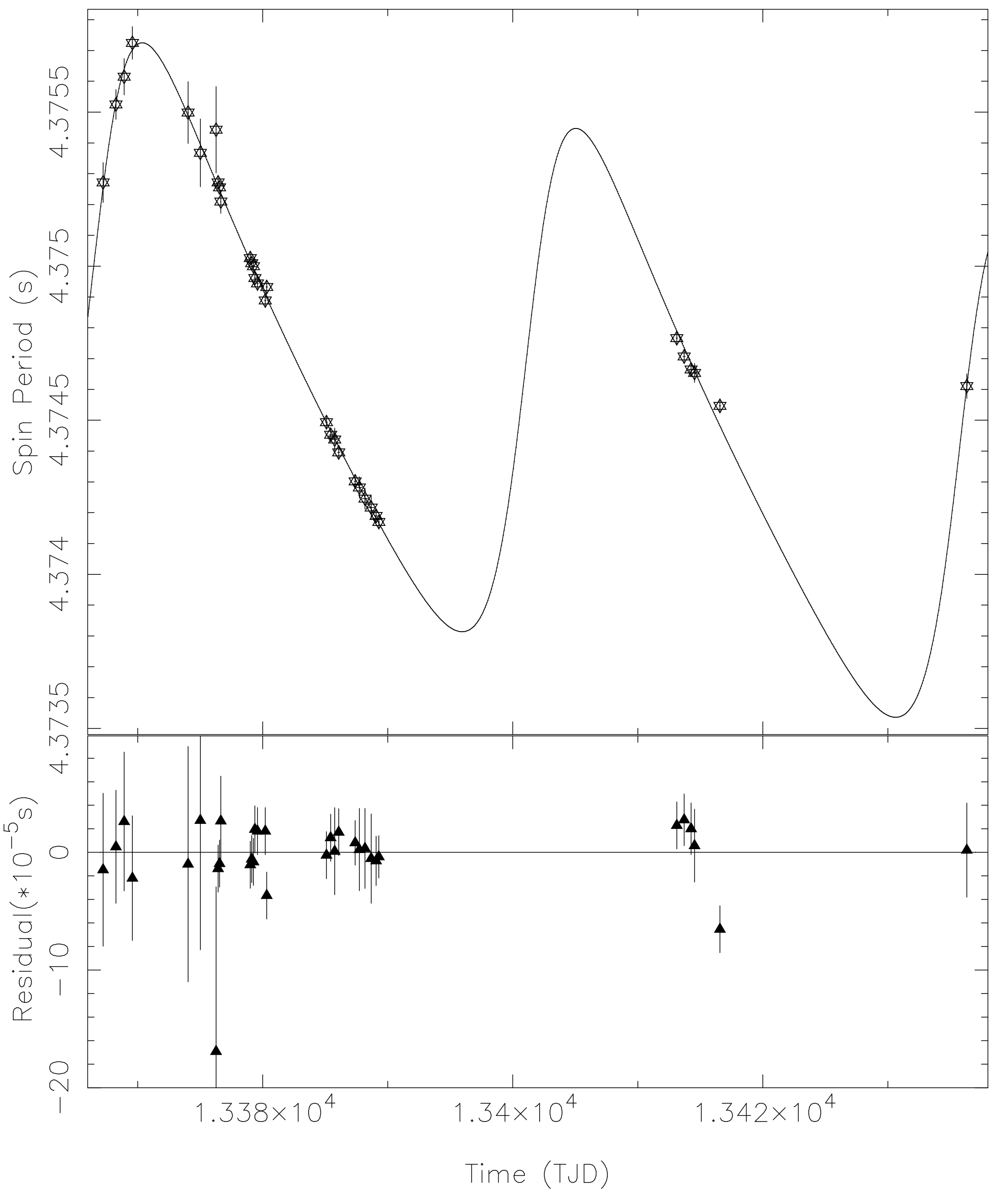

Fig. 2.— Doppler effect on the spin period (the symbols of the stars in the upper panel) and the curve with the best-fit orbital parameters (upper panel). The corresponding residuals are shown in the lower panel.

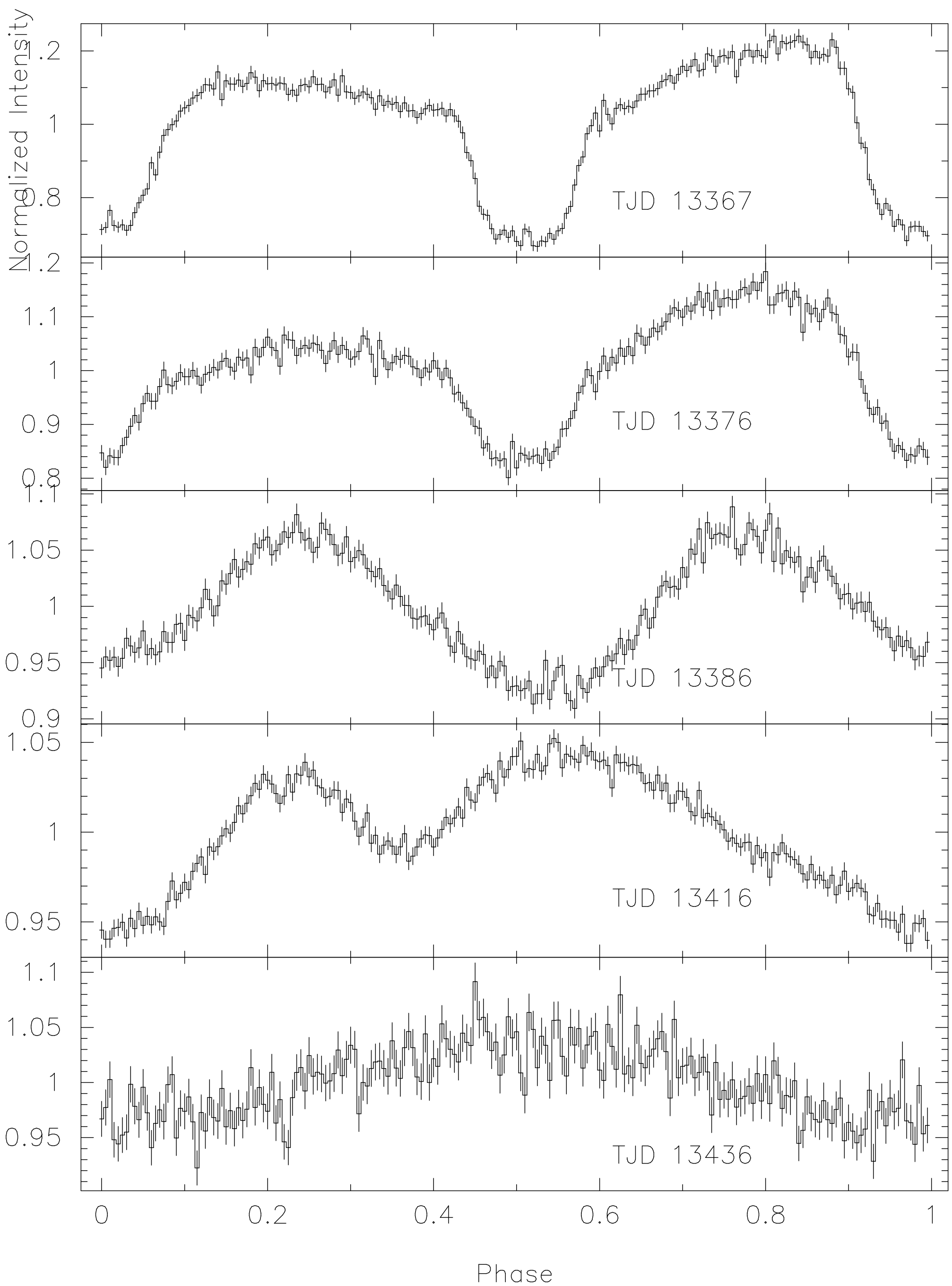

Fig. 3.— The typical light curves at different intensity level of V0332+53 during the outburst.